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ACOUSTIC SEAMOUNT RANGING WITH EXPLOSIVE CHARGES. (U)

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U. S. NAVY ELECTRONICS LABORATORY
SAN DIEGO 52, CALIFORNIA

TECHNICAL MEMORANDUM

ACOUSTIC SEAMOUNT RANGING WITH EXPLOSIVE CHARGES

By R. Halley

INTRODUCTION

This memorandum is intended for the use of others at NEL and a few outside the laboratory with particular interest in seamount ranging. It is for their information only and is not a formal report on a laboratory project.

The problem of topographic mapping of the ocean floor has been a matter of interest to the Navy and to oceanographers for many years. Throughout this period there has been the need for a method of survey to supplement the normal sounding techniques. The use of acoustic systems which would detect major irregularities in the ocean bottom by virtue of their reflection of sound from explosive charges has been proposed many times and limited experiments in the use of this technique have been made.[1]

The analysis of acoustic measurements made in connection with the atomic explosion of Operation WIGWAM in 1955 showed that reflections were being received from islands and major seamounts throughout the greater part of the Pacific Ocean.[2] Computations further showed that

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1. B. Luskin, M. Landisman, G. B. Tirey, and G. R. Hamilton, "Submarine Topographic Echoes from Explosive Sound", Bull., Geol. Soc. Amer. 63: 1053-1068 (1952)

with proper instrumentation surveys could be carried out over a radius of four or five hundred miles, using source charges on the order of hundreds of pounds of TNT.

Operation CHINOOK, conducted by Scripps Institution of Oceanography in the summer of 1956, afforded an opportunity to test these conclusions. It was recognized that due to the limited time available for preparation this would be a very rough test which at best would probably provide valuable experience upon which to base requirements for future programs. It was necessary to make use of existing facilities almost exclusively and to conduct the tests on a not-to-interfere basis with the primary missions of the cruise. Again due to time limitations it was impossible to carry out an adequate analysis of the experimental situation in advance. Recognizing these handicaps it was decided that the low cost of the experiment made it worthwhile to go ahead and see what could be learned from the experience. Although the results of the experiment were extremely disappointing from the standpoint of seamount location the experience was valuable in indicating the requirements which must be met for successful operation of such a survey.

Operation CHINOOK involved an oceanographic survey of the North Pacific conducted by two Scripps ships, the R/V STRANGER and the R/V SPENCER F. BAIRD. The general track covered by the two ships is shown in figure 1. The operational plan called for the BAIRD to set off six 320-pound TNT charges at the axis of the deep sound channel while the

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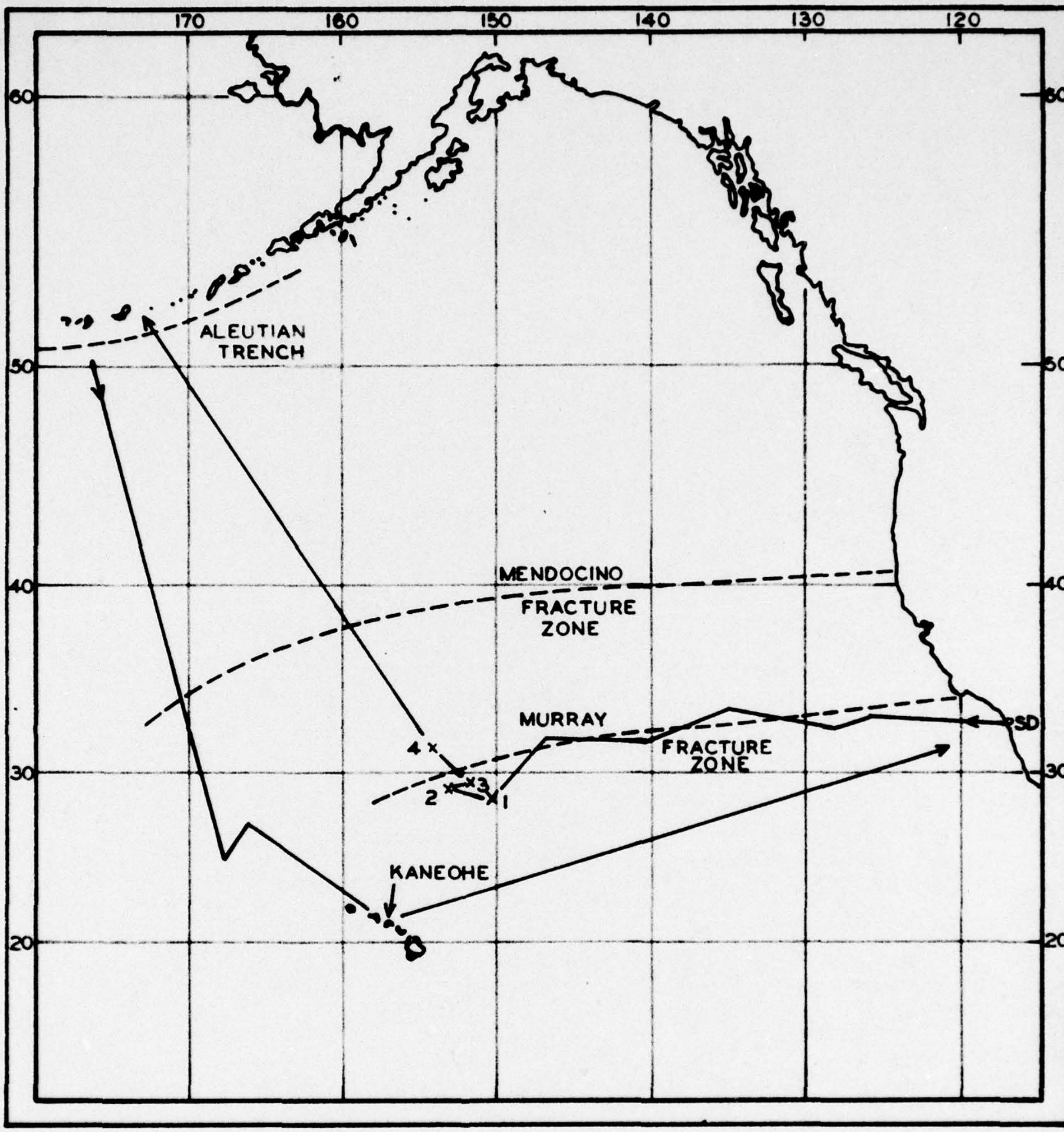
2. M. J. Sheehy and R. Halley, "A Measurement of the Attenuation of Low-Frequency Underwater Sound", JASA, Vol. 29 (1957)



170
160
150
140
130
120
60
50
40
30
20
ALEUTIAN
TRENCH
MENDOCINO
FRACTURE
ZONE
MURRAY
FRACTURE
ZONE
4
3
2
1
KANEOHE
SD

FIGURE 1

ships were still in southern latitudes near Hawaii. Four such charges were actually exploded at the points shown by the stars numbered 1 to 4 in figure 1. It was also planned that at the time of each explosion the ships would be approximately fifty miles apart and that the acoustic signal from the explosion would be monitored by each ship for a period of about half an hour after each shot. A third monitoring station was manned at the former SOFAR station at Kaneohe, Oahu, T. H.

The listening system at Kaneohe has been adequately described before[3] and the description will not be repeated here. A single type 14D3X hydrophone, bottom mounted at a depth of about 350 fathoms was used for this test. The system was in good operating condition and performed as expected. Magnetic tape records of each shot and the period of about half an hour following were made for later analysis.

The receiving system on the STRANGER used a single type AX58 hydrophone out of an array used for seismic recording. The hydrophone was at a depth of about 200 feet, buoyed and floated away from the ship. During the recording period the ship was lying to with all major machinery units secured. System sensitivity was good and self noise was low. Good records were also obtained from this receiver.

On the BAIRD a single AX58 type hydrophone was also used. It was suspended from the side of the ship at a depth of about 200 feet. the procedure followed was to drop the TNT charge while underway and then to bring the ship to a stop at a point about half a mile from the drop point. The hydrophone then had to be rigged out and the

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3. NEL SOFAR Research Group, "Triangulation Tests of the Northeast Pacific SOFAR Network", NEL Report 175 (27 April 1950)

recording started. In no case was this accomplished in time to record the initial explosion although the explosion was heard through the hull of the ship and the time noted. Under these circumstances it was not possible to quiet the BAIRD sufficiently for the echoes to be detected in the noise and no useful records were obtained.

Accurate timing was maintained on the BAIRD's shot records and on the recordings made by the STRANGER and at the Kaneohe station by recording time signals from WWVH.

COMPUTATIONAL METHODS

Before examining the results obtained from the records of this experiment let us examine the general problem of determining the location of multiple reflectors from such records. In general, two receivers such as were operating during this test are not sufficient to obtain the locations of multiple reflectors from a single charge so we will examine the more reasonable situation where three receivers are used.

Let us assume that a suitable charge is set off in an area containing many reflectors and that signals are received at three separate receivers. Now a number of echo signals will be received at each receiver and there is no way of associating any single echo at one receiver with any particular echo at any other receiver. Hence, all possible pairings which do not lead to imaginary solutions must be considered. This means that for any two receiving stations all signal pairs must be considered for which the time difference of arrivals is not greater than the sound travel time between the two stations. Hence

two receivers fairly close together would require far fewer computations and lead to far fewer false solutions than two widely separated receivers. This problem of system saturation has previously been considered in detail.[4] Conversely however, in the interests of accuracy the receivers should be well separated, and considering the aims of any given survey a judicious choice of receiving locations must be made.

Let us now assume that there is only a single reflector in the area and consider the methods by which its location may be obtained. We must keep in mind, however, that any method selected must be iterated perhaps hundreds of times in analyzing the records from a single explosion.

Figure 2 illustrates the general situation for a source (S), a reflector (R), and three receivers (A, B, and D), all on the surface of a sphere. ϕ and θ are coordinates of latitude and longitude in terms of which we have $R = (\phi, \theta)$; $S = (\phi_S, \theta_S)$; and $A = (\phi_A, \theta_A)$, etc.

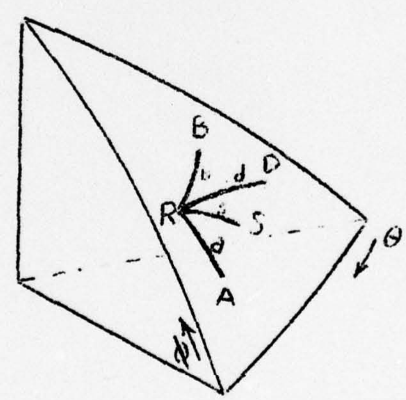

FIGURE 2

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4. R. W. Rempel, "Some Signal Inversion Probabilities in the Northeast Pacific SOFAR Network". NEL Report 303. (June 1952)

The lines, a, b, d, and s, all represent sound travel paths measured in terms of great circle arc. If the detonation time of the source is known and taken as $t = 0$ and the arrival times of the echoes at the three receivers are t_A, t_B, and t_D, and we further specify the total sound travel distances to each of the three receivers in terms of great circle arcs as T_A, T_B, and T_D then it is apparent that the reflector R must lie at the point where the three conditions

$$T_A = a + s \tag{1}$$

$$T_B = b + s \tag{2}$$

$$T_D = d + s \tag{3}$$

are true simultaneously. This obviously defines the common point of intersection of three "ellipses"; i. e., three curves each of which is the locus of points the sum of whose great circle distances from two fixed points is a constant. The three equations are independent and although any pair of these "ellipses" may intersect in as many as four points there should be only a single common point of intersection of all three curves except in very unusual cases of symmetry.

Now if either the time of explosion or location of the source is unknown we may immediately eliminate s from these equations and have two independent equations such as

$$T_A - T_B = a - b \tag{4}$$

and

$$T_A - T_D = a - d \tag{5}$$

The simultaneous solution of these equations will yield the points of intersection of two "hyperbolas"; i. e., two curves each of which is the locus of points for which the difference between the great circle distances from two fixed points is a constant. With only two independent equations there will in general be two real solutions with no means of choosing between them. Therefore, it becomes mandatory that either the source data be known or that four separate receivers be used to remove ambiguities in the solution.

Let us continue to assume three receivers and known source data and consider further the means of obtaining solutions to equations (1), (2), and (3) in terms of the two independent coordinates θ and ϕ. Expanding equation (1) we have

$$\cos T_A = \cos (a + s) = \cos a \cos s - \sin a \sin s \tag{6}$$

where $\cos a = \cos (\theta_A - \theta) \cos (\phi_A - \phi)$ (7)

and $\cos s = \cos (\theta_S - \theta) \cos (\phi_S - \phi)$ (8)

It is obvious that further expansion of this equation will result in an extremely complex trigonometric expression whose inclusion here would serve no useful purpose. It is presumed however that such a pair of expressions could be solved simultaneously after sufficient algebraic manipulation. The resulting solutions will themselves be so complex in form that it would be foolish to consider their numerical solution in the number of cases required by the problem without recourse to at least

a medium speed computer. Since it is our goal here to find a method of solution which will not require the availability of such a device we will continue to consider means to simplify the solution of the problem.

The first and most obvious means of simplification is to choose the coordinate axes for any particular explosion in such a fashion as to make as many factors as possible equal to zero. It may simply be stated that while this obviously simplifies the expressions involved it is not sufficient to materially change the manner or complexity of solution.

A second and extremely effective means of simplifying the problem is to assume that the source is located at one of the receivers. This has the further advantage of being most convenient as a means of conducting the experiment.

Consideration of figure 2 shows that if the source is located at one of the receivers s becomes equal to the distance (a, b or d) from that receiver to the reflector and that distance is simply half of the total sound travel distance measured at that receiver. By substitution for s in equations (1), (2) and (3) we find that a, b and d are each equal to a known combination of values of the measured sound travel distances. The three equations now define three circles of radius a, b and d with corresponding centers at A, B and D and with a common intersection at the reflector. Graphical solution of the three equations would now be extremely convenient providing one had a sufficiently large spherical surface upon which to work. Combining this assumption with a judicious choice of coordinates a solution can be written out in fairly

simple form which would be amenable to handling on a punch card computer or even by hand computation for a limited number of cases. This solution is developed in appendix 1.

As a final simplification let us now consider the effects of approximating the spherical surface by orthographic projection on a plane. Such an approximation must obviously lead to errors in the solution, so let us first examine the size of the errors involved and determine if such an approximation is feasible.

In studying the acoustic records we are able to measure the time of arrival of reflected signals to an accuracy of about $\pm$ 1 second or say $\pm$ 1 nautical mile. Seamounts large enough to produce useful reflections must extend over some reasonable area, say three to five miles. Further, accurate location is unnecessary since any seamount so indicated will be subject to further detailed bathymetric study. Let us then say that $\pm$ 3 miles is sufficient accuracy for location, and that $\pm$ 2 miles of this may be tolerated in the approximation due to the plane projection. Now the error of approximation on the plane projection is simply the difference in distance between the spherical arc and the projected chord. This error may then be written

$$e = r\,(\alpha - \sin\alpha) \tag{12}$$

where α is the arc distance, and r is the radius of the sphere. For an error of e = 2 miles, we find α = .145 radians, or almost exactly 500 miles. Thus, if we choose the point of projection at the source, all points of interest must lie within about 500 miles of this point. This seems to be reasonable area in which to work and the approximations may be considered feasible.

Now in attempting to make a computational solution on the plane the form of equations (9), (10) and (11) will remain unchanged, but the solution must be made in rectangular coordinates. If one again makes a judicious choice of coordinate systems, the solution has about the same computational complexity as the spherical solution of appendix 1. Thus the approximation offers no new advantages and increases the complexity of transforming the solution back to the geographic coordinates, (θ, ϕ).

However, if we investigate the effect of the approximation on the solution of the equations by graphical means, we find that we may now obtain solutions simply by drawing circles on a plane. The error of approximation is apparent here in that the circles will not be a true representation of the circles on a sphere and they will no longer intersect at a single point, but at three closely scattered points. For a true solution it is necessary, but not sufficient, that these three points should lie within a circle of a three-mile radius. Thus we must expect even more spurious solutions. This method should prove valuable, however, for a rapid analysis of results if the radius of the circle of interest is limited to 500 miles, if the number of reflections received at each station is limited in number and spaced many seconds apart, and if the circles are drawn on a chart made either by orthographic projection or by a Lambert conformal conic projection.

In summation of this section we may say that from the standpoint of ease of computation it is advisable to locate the source at the same point as one of the receivers. With this assumption and by proper choice of coordinate systems it is possible to express the solutions in sufficiently simple form for punch card calculation or even for hand calculation of a limited number of reflections. Finally, by projecting restricted areas of

the spherical surface onto a plane it is possible to obtain approximate solutions by graphical means by the simple process of drawing circles of appropriate radius about the three receivers.

RESULTS

It is unfortunate that the short time available for preparation for this exercise did not allow the theoretical considerations outlined above to be made until after the completion of the exercise. The desirability of having the source and one receiver at the same location was recognized, but it was not realized how completely this factor dominates the choice of methods of solution. Special shipboard instrumentation for this exercise could be prepared only in very limited form and consequently instrumentation available on the ships for other purposes was used to a great extent. Since the M/V STRANGER was being used throughout the operation as the receiving ship in seismic profile runs, she was well instrumented to act as a receiver for the seamount ranging exercises. The BAIRD, which was to act as the source ship and to drop the explosive charges, was not so instrumented and it was possible to install only the most rudimentary listening apparatus for use in this exercise. The low sensitivity of this system, coupled with the extremely high self-noise levels of the BAIRD, resulted in no useful information being recorded at this station. The BAIRD station did record the direct signal from the charge and these data were available for use in computing explosion times. The receiving system on the STRANGER and at Kaneohe operated satisfactorily and reflected signals were recorded at both stations with time delays up to twenty minutes following the reception of the direct signal. Consequently we had four pairs of recordings available for analysis. The ti e sequence

of echoes on these four record pairs is shown in figure 3 together with the total number of echoes observed on each record.

It must be noted that this figure includes every signal received at either receiver within 2,000 seconds of the detonation time which could possibly arise by reflection of the signal from the explosive charge. In general these signals were small. None were more than 10 db and most were less than 5 db above noise in the best third-octave band. It is considered that a large percentage of these signals may have been spurious.

From the computational methods developed above, it may be seen that we were left in a very unfavorable position for computing the locations of the reflectors represented by the received echoes. The only method of solution available to us without the services of a large computer was to attempt graphical solution by means of ellipses drawn on the plane approximation to the sphere. Knowing the location and detonation time of the source, the location of the receiver, and time of reception of the echoes, it was possible to draw one ellipse for each echo which would represent all the possible points of reflection. Since there was no way of pairing echoes received at the two stations, and since two signals from any one reflector are insufficient to determine position uniquely, the only way to get reliable solutions was to plot every possible ellipse for all four shots on a single sheet and to depend upon the consistent appearance of a real reflector to cause a number of intersections to occur at the same point.

It is then necessary to consider the accuracy of the measurements and approximations in order to determine what will be considered as intersection at the "same point". Considering the approximations involved,

it was determined that we could expect nothing better than an accuracy of ± 3 miles even under ideal conditions. A consideration of the results of drawing the 145 necessary ellipses indicated that there would be several hundred cases where two intersections could be considered to occur within the three-mile limits. At this point it was necessary to inquire into the navigational accuracy which determined the accuracy of locating the foci of the ellipses.

A simple check was available by comparing the distances from the source to the receivers as computed from navigational data with that computed from acoustic data. The results of this comparison are shown in table 1.

TABLE 1

COMPARISON OF COMPUTED DISTANCES
BAIRD to Kaneohe
Nautical Miles

Shot Number	Acoustic Distance	Navigational Distance	Differences
2	582	615	34
3	502	518	16
4	540	559	19
5	602	608	6
			Mean 19

BAIRD to STRANGER
Nautical Miles

2	74.4	75.	0.6
3	39.2	42.	2.8
4	6.4	4.1	-2.4
5	55.2	66.	10.8

The tremendous errors indicated by this comparison made it obvious that any further attempts to compute reflector positions were doomed to failure. Before abandoning the problem entirely, however, consideration was made of the fact that the errors appear consistently with the same sign and thus the differences might be due to an erroneous assumption as to the velocity of sound propagation in the deep sound channel. If the mean sound velocity were to be adjusted to account for the mean difference of nineteen nautical miles in the position measurements between the BAIRD and Kaneohe, a mean sound velocity of 5,019 feet per second would have to be used. This is far greater than any value ever observed for deep sound channel propagation. Even if it were a more believable figure, the variation in range differences of thirteen and fifteen miles below and above the mean would still be unexplained. Velocities computed for the BAIRD to STRANGER variations are even worse, about 5,200 feet/second, but because of the shorter travel paths, this computation is less reliable.

It may be added that years of experience with SOFAR experiments have indicated that for bombs dropped in this area the acoustic range error at the Kaneohe station should be under two miles. An unsuccessful attempt was made to compute better ship positions from the accumulated navigational data. Since these data errors precluded the possibility of successful determination of reflector positions, no further attempts were made.

CONCLUSIONS

1. The results of the WIGWAM recordings remain as evidence that explosive echo ranging of seamounts should be feasible.

2. Theoretical considerations indicate that, with a well designed experiment, calculation of reflector position can easily be made by a punch card computer. Location of the source and one of the receivers at the same point will materially simplify these computations. Under these same conditions approximate solutions by relatively simple graphical means are possible.

3. The relatively small signal-to-noise ratios observed during the present experiment indicate that the charge size used may have been insufficient for the purpose and that it should be increased to provide an additional 5 - 10 db of signal level in the water. On the other hand, there were no known reflectors in the area under study and the low signal strength may have been due to our absence of suitable reflectors.

RECOMMENDATIONS

1. This experiment should be repeated under more carefully controlled conditions. At least the following improvements should be effected.

a. A source and three receivers should be provided. The receiving ships should be quieted and listening systems should be installed which normally record ambient water noise in the frequency range of 200 - 1,000 cps.

b. The source should be detonated at the position of one of the receivers.

c. The ships should be provided with modern navigational aids and the experiment conducted in an area which will allow navigational

accuracies of ± one mile.

d. The area of investigation should be restricted to a circle of not more than five hundred miles' radius around the source. The ships should be spaced in a triangle about one-hundred fifty miles on a side.

e. The area of investigation should be chosen as one which is neither essentially free from known seamounts nor as one which is known to be cluttered with seamounts.

f. If signal levels are still low in an area containing known reflectors, the charge size should be increased to give about an additional 5 to 10 db of source level.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Mr. C. N. Miller of NEL who performed the measurements onboard the STRANGER and to Mr. A. R. Sherwood of SIO who made the measurements onboard the BAIRD and reduced the experimental data. He is also indebted to Dr. George Shor of SIO, the Senior Scientist for Operation CHINOOK, and to the officers and crews of the STRANGER and BAIRD, without whose cooperation the experiment could not have been performed.

APPENDIX 1

COMPUTATIONAL SOLUTION IN ANGULAR COORDINATES WITH THREE RECEIVERS WITH THE SOURCE AT ONE RECEIVER

Let us first define a new set of orthogonal coordinates which will make the computations more convenient than they are with coordinates of latitude and longitude. Of course the solutions must be transposed back to latitude and longitude before they can be specified in standard navigational terms.

Let us choose a set of orthogonal coordinates (α, β), identical with (θ, ϕ) except that the origin is located at Point A and the system is rotated through an angle, γ, so that the coordinate, $\beta = 0$, passes through Point B. We then have the following relationships between the two coordinate systems

$$\theta = \theta_A + \tan^{-1}\left[\tan\alpha \cos\gamma\right] - \sin^{-1}\left[\sin\beta \sin\gamma\right] \qquad (1')$$

$$\phi = \phi_A + \sin^{-1}\left[\sin\alpha \sin\gamma\right] + \tan^{-1}\left[\tan\beta \cos\gamma\right] \qquad (2')$$

$$\tan\gamma = \frac{\tan\left[\phi_B - \phi_A\right]}{\sin\left[\theta_A - \theta_B\right]} \qquad (3')$$

Now since the three travel distances, a, b, and d, are each equal to a known combination of measured travel distances which we may designate for the moment as T_1, T_2 and T_3, we may write

$$a = T_1 \qquad (4')$$

$$b = T_2 \qquad (5')$$

$$d = T_3 \qquad (6')$$

In terms of the (α, β) coordinate system we may then write

$$\cos T_1 = \cos \alpha \cos \beta \tag{7'}$$

$$\cos T_2 = \cos (\alpha_B - \alpha) \cos \beta \tag{8'}$$

$$\cos T_3 = \cos (\alpha_D - \alpha) \cos (\beta_D - \beta) \tag{9'}$$

solving equations (7') and (8') simultaneously, we obtain

$$\tan \alpha = \frac{\dfrac{\cos T_2}{\cos T_1} - \cos \alpha_B}{\sin \alpha_B} \tag{10'}$$

and

$$\cos \beta = \frac{\cos T_1}{\cos \alpha} \tag{11'}$$

In general this gives two principal values for α, one of which will be close to $\alpha = 0$ and the other will differ from it by 180 degrees, and will be completely unreasonable. For the one reasonable value of α there will be two values of β, neither of which can be discarded without further examination.

Solving equation (9') for $\cos \beta$ we have

$$\cos \beta = \frac{\cos T_3 \cos \beta_D}{\cos (\alpha_D - \alpha)} \pm \sin \beta_D \left[1 - \frac{\cos^2 T_3}{\cos^2 (\alpha_D - \alpha)} \right] \tag{12'}$$

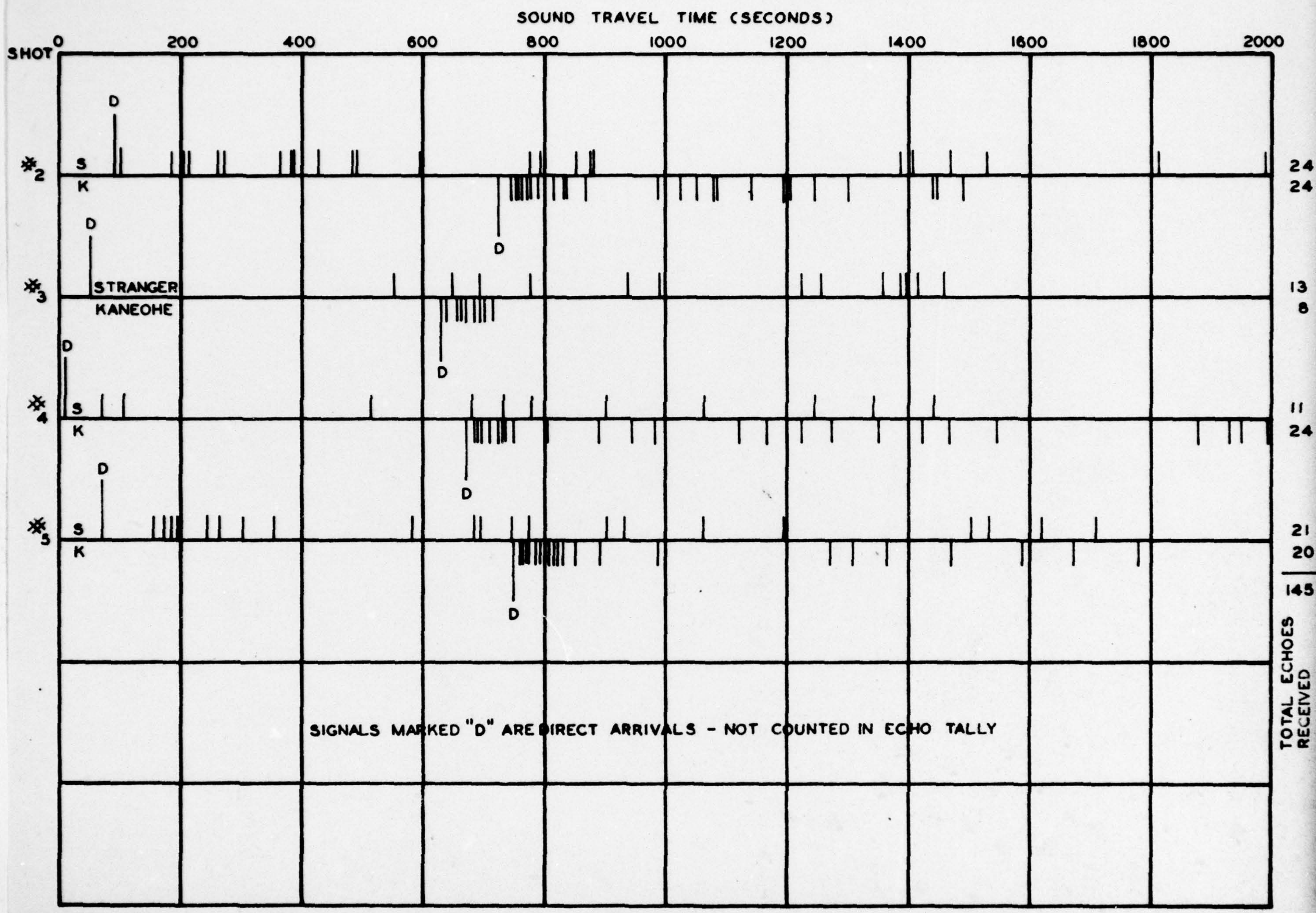
If we now substitute the chosen value of α from equation (10') into equation (12') we obtain two new values of β only one of which should agree closely with one of the values found by equation (11'). Choosing this value we now have a unique solution in terms of (α, β).

It must be remembered that this solution will still not represent a true reflector unless the signals arriving at the three receivers have been properly grouped. Thus we shall in most cases have many spurious solutions. The validity of the solutions can only be checked by repeating the experiment with a charge dropped at another location.

Fortunately, we have not yet designated any of the receiving points as the source point. Consequently, we may use the equations and coordinate system for charges from any of the points simply by inserting the proper values for T_1, T_2, and T_3 into the equations according to the following table.

	SOURCE POINT		
	A	B	D
T_1	$\frac{T_A}{2}$	$T_A - \frac{T_B}{2}$	$T_A - \frac{T_D}{2}$
T_2	$T_B - \frac{T_A}{2}$	$\frac{T_B}{2}$	$T_B - \frac{T_D}{2}$
T_3	$T_D - \frac{T_A}{2}$	$T_D - \frac{T_B}{2}$	$\frac{T_D}{2}$

Thus, if charges are dropped from each ship at, say, one hour intervals, we can obtain three independent sets of solutions (only two of which are necessary) and thus pick out the solutions corresponding to real reflectors before making the transformation back to latitude and longitude (θ, ϕ) through equations (1'), (2'), and (3').



SOUND TRAVEL TIME (SECONDS)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
SHOT
#2
S
K
D
24
24
#3
STRANGER
KANEOHE
13
8
#4
S
K
11
24
#5
S
K
21
20
145
TOTAL ECHOES RECEIVED
SIGNALS MARKED "D" ARE DIRECT ARRIVALS - NOT COUNTED IN ECHO TALLY

FIGURE 3